The dynamics of voiceless sibilant fricative production in children between 7 and 13 years old: An ultrasound and acoustic study

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(Received 17 May 2018; revised 11 August 2018; accepted 23 August 2018; published online 19 September 2018)

This study reports on dynamic tongue shape and spectral characteristics of sibilant fricatives /s/ and /ʃ/ in Scottish English speaking children aged between 7 and 13 years old. The sequences /əCa/ and /əCi/ were produced by 40 children, with ten participants in each age group, and two-year intervals between successive groups. Productions of the same sequences by ten adults were used for comparison with the children's data. Quantitative dynamic analyses were carried out on spectral information and on ultrasound imaging data on tongue shape. All age groups differentiated between the two consonants in the fricative centroid and in tongue shape. Vowel-on-consonant effects showed consonant-specific patterns across age groups without a consistent increase or decrease in the extent of coarticulation with increasing age. The extent of discriminability between the two fricatives increased with age on both acoustic and articulatory measures. Younger speakers were generally more variable than older speakers. Complementary findings from the centroid and tongue shape measures suggest that age-related differences are due to the ongoing maturation of controlling the tongue in coordination with other articulators, particularly the jaw, throughout childhood.
 https://doi.org/10.1121/1.5053585

[BVT] Pages: 1454–1466

I. INTRODUCTION

Sibilant fricative consonants are acquired by English speaking children with typically developing speech relatively late (see, e.g., McLeod, 2013, for a review of developmental studies focused on English spoken in the United States, Australia, England, and Scotland). A number of studies have reported that during the speech sound acquisition process, English speaking children have less differentiation between correct productions of /ʃ/ and /s/ than adults (e.g., Nittrouer *et al.*, 1989; Holliday *et al.*, 2015; Maas and Mailend, 2017), a process also observed in other languages (Li *et al.*, 2009; Reidy, 2015, for Japanese; Kleber, 2015, for German; Li and Munson, 2016, for Mandarin Chinese). Despite the fact that both /s/ and /ʃ/ are generally perceptually adult-like by the age of seven years old, differences in lingual articulation between child and adult productions have been observed beyond this age (Zharkova, 2016; see also Koenig *et al.*, 2008), and it has been suggested that such differences persist into early adolescence (Romeo *et al.*, 2013). This is not surprising given that even the development of temporal-spatial control of the lips, which have fewer degrees of freedom than the tongue (see, e.g., Beautemps *et al.*, 2001), has been shown to be protracted compared with that of controlling the jaw (Green *et al.*, 2000), continuing during the adolescent years (see Smith, 2013, and references cited there). Studies using articulatory information from tongue movements have not yet described in detail the development of the sibilant contrast throughout childhood. The present study describes the production of sibilant fricatives in four successive age groups of Scottish English speaking children aged 7, 9, 11, and 13 years, in comparison with adults. The analyses were carried out using acoustic data and direct information on tongue shape from ultrasound imaging. The study focused on cross-consonant differences as well as effects from contrasting vowels on the two fricatives and age-related differences in variability of the fricatives.

A number of studies have demonstrated that dynamic analyses of fricative consonants, focusing on the changing pattern in the time domain, provide a more complete characterisation of the consonant production in adults (e.g., Iskarous *et al.*, 2011) and in children (e.g., Munson, 2004; Reidy, 2015; Zharkova, 2016) than analyses of selected time points. Therefore, the analyses in this study included spectral and tongue shape information throughout the target fricative consonant. We applied $LOC_{a\text{-}i}$ index, which is a ratio of the excursion of the tongue front to that of the tongue back (Zharkova *et al.*, 2015), to midsagittal ultrasound imaging data. Zharkova (2016) showed that $LOC_{a\text{-}i}$ is a reliable indicator of differences between /s/ and /ʃ/ in adults and preadolescent children. We chose this articulatory index because using it allowed us to make comparisons with our previous work on fricative articulation (e.g., Zharkova, 2016, 2018), and, importantly, to provide information that could be used in future studies of fricative dynamics in younger children. $LOC_{a\text{-}i}$ has been demonstrated to provide robust results on ultrasound data collected without head-to-transducer stabilisation (Zharkova *et al.*, 2015). This is crucial for analysing data from young children, as well as from people with motor

 0001-4966/2018/144(3)/1454/13/$30.00

disorders, when adequate stabilisation is impossible to achieve (see the last paragraph of the paper for further discussion). We are not aware of any other articulatory indices quantifying the difference between /s/ and /ʃ/ that would be suitable for use with non-head-stabilised ultrasound data. $\mathrm{LOC}_{a\text{-}i}$ can also provide information on the location of tongue bunching along the tongue contour across contrasting vowel contexts (see Zharkova *et al.*, 2015, for the description of this index as a measure of vowel-related coarticulation).

The change in spectral properties during the fricative was measured in this study using centroid frequency of the consonant spectrum, which distinguishes between /s/ and /ʃ/ in English speaking adults and children (e.g., Forrest *et al.*, 1988; Nittrouer *et al.*, 1989). The centroid was chosen in this study because it is often used to describe the production of these two consonants (e.g., Jongman *et al.*, 2000; Li *et al.*, 2009; Holliday *et al.*, 2015), and it has been shown to be related to other spectral measures of sibilant fricatives (e.g., Iskarous *et al.*, 2011; Romeo *et al.*, 2013). The fricative centroid is also in a known relationship with $\mathrm{LOC}_{a\text{-}i}$. Specifically, in a study of /s/ and /ʃ/ production by adults and preadolescents, $\mathrm{LOC}_{a\text{-}i}$ and the fricative centroid were shown to be significantly and negatively correlated, throughout the duration of the consonant (Table IV in Zharkova, 2016). At the same time, these measures provide complementary information. Since $\mathrm{LOC}_{a\text{-}i}$ quantifies aspects of midsagittal tongue shape, discrepancies between $\mathrm{LOC}_{a\text{-}i}$ and centroid patterns can make it possible to separate midsagittal tongue activity from that of other articulators, such as the jaw, the lips, or the sides of the tongue. In this study, we expected that adults, adolescents, and 11-year-olds would have reliable differences between the fricatives in $\mathrm{LOC}_{a\text{-}i}$ and in the centroid, throughout the consonant. The two youngest groups of children were also expected to differentiate between the fricatives, although potentially less than the older groups (see Nittrouer *et al.*, 1989; Nittrouer, 1995; Romeo *et al.*, 2013).

Since vowel-on-fricative effects have previously been reported for all child age groups addressed in this study, using acoustic and articulatory methods (see Zharkova, 2018, for a review), we analysed vowel-related influence on both consonants produced by our speakers. In this study, we expected at least some vowel-related coarticulation in all age groups, as well as differences in lingual coarticulation across the two consonants (see Recasens and Rodríguez, 2017). The extent of coarticulation within a consonant-vowel (CV) syllable has often been interpreted as an indicator of the size of the planning unit in children and adults, with more versus less intra-syllabic coarticulation indicating the use of larger versus smaller units of production, respectively (see Nittrouer *et al.*, 1989). However, it has not been possible, to date, to find unequivocal support for this idea, since the results on age-related changes in the extent of coarticulation vary strongly across studies, and, importantly, across speech segments. Drawing particularly on previous reports of age-related segment-specific tongue movement patterns in studies of vowel-on-consonant anticipatory coarticulation, we could instead interpret the observed coarticulation patterns as follows: "age-related differences in motor programming may depend not on whether the units are syllables or segments but on the nature of the task to be performed by the articulators in each case" (Zharkova *et al.*, 2014, p. 384). This interpretation is supported by acoustic results from Reidy (2015), showing contrasting developmental patterns of vowel-on-fricative coarticulation, depending on the articulators involved. Reidy concludes that "vowel-context effects indicate only the maturation of the ability to coordinate gestures that involve different articulators" (p. 139). Relating this approach to our study, any age-dependent consonant-specific patterns of anticipatory coarticulation would indicate developmental changes in controlling the articulators involved in the fricative production. We used a subset of the child dataset described in Zharkova (2018). That study, which focused on vowel-on-consonant effects at mid-consonant, observed adolescent-like $\mathrm{LOC}_{a\text{-}i}$ patterns for the stops /p/ and /t/ starting from the age of three and nine years old, respectively, while evidence of any vowel-on-fricative coarticulation on this measure was only reported for the adolescents. The study, however, did not analyse the dynamic patterns of tongue shape change, nor did it report any spectral characteristics of the target consonants.

Fricative consonant production has been shown in acoustic studies to exhibit more within-speaker variability in children during preschool and early primary school years than in adults (e.g., on duration: Munson, 2004; on spectral characteristics: Romeo *et al.*, 2013; Holliday *et al.*, 2015). Articulatory information from ultrasound data on tongue position has also demonstrated larger-than-adult variability in children, for example, at the mid-point of voiceless fricatives produced by six-to-nine-year-old speakers of Scottish English (Zharkova *et al.*, 2011, 2012). Within-speaker variability in tongue shape at mid-consonant has been shown to be reduced between three years old and early adolescence (Zharkova, 2018; see also Barbier, 2016, showing increased variability in tongue position of stop consonants in four-year-old children, compared with adults). Similar-to-adult within-speaker variability in tongue position during fricative production has been reported in 10–12-year-old children (Zharkova *et al.*, 2014), although results from fricative centroid measurements averaged over the middle 50% of the consonant as well as over its total duration suggest that there may be further developmental differences even beyond this age (Romeo *et al.*, 2013; Zharkova, 2016). In the present study, we quantified within-speaker variability throughout the fricative duration, and a reduction in variability with increasing age was expected.

In summary, the study aimed to assess cross-consonant differences, as well as vowel-related coarticulatory differences in both consonants, and within-speaker variability in the realisation of the target fricatives. We expected to observe increased differentiation between /s/ and /ʃ/ in older age groups as well as age-related consonant-specific coarticulatory patterns, and a reduction in within-speaker variability with increasing age.

II. METHOD

The speakers were 40 typically developing children with no known speech or hearing disorders, as determined by parental report. There were ten participants in each of the following age groups: 7-year-olds (6;11 – 8;2 [years;-months], 9 boys), 9-year-olds (9;0 – 9;9, 5 boys), 11-year-olds (11;0 – 11;10, 3 boys), and 13-year-olds (13;0 – 13;11, 4 boys), all native speakers of Scottish Standard English. The children produced the syllables /ʃi/, /ʃa/, /si/, and /sa/, in the carrier phrase "It's a…, Pam," with five repetitions of every target (the syllables /pi/, /pa/, /ti/, and /ta/ were also recorded; those data are not reported in this paper). The data from five repetitions of the same stimuli, produced by ten adult speakers (three men), with the same experimental setup, were chosen from a larger dataset described in Zharkova *et al.* (2014) and Zharkova (2016). The adult speakers whose data were used in this study were aged between 26 and 48 years old, with the average age of 38 years old. Productions of all stimuli were judged by the first author as perceptually accurate English versions of the target sounds. Most of the seven-year-old participants were boys, and boys have been reported to have more speech errors than girls (e.g., a higher error rate in English speaking boys was reported for dental fricatives in children between 5 years 6 months and 6 years 11 months, by Dodd *et al.*, 2003). However, since we only analysed perceptually accurate tokens of the target consonants, the issue of gender differences related to potential speech errors in the youngest age group is not relevant for our study.

During the recording of the child participants, the children sat in front of a computer display, which presented the stimuli to them in English orthography, accompanied by images corresponding to the target CV syllables. The syllables were spelled as "she," "shah," "sea," and "Sah"; the image for "Sah" was that of an imaginary creature. Before the recording, the children were familiarised with the target sentences and images. Tongue movements in the midsagittal plane were recorded using an Ultrasonix Sonix RP ultrasound scanner with a C9-5/10 microconvex transducer, and Articulate Assistant Advanced software (Articulate Instruments Ltd, 2012). The ultrasound frame rate was 100 Hz. The acoustic signal, synchronized with the ultrasound signal, was recorded at 22 050 Hz using an Audiotechnica AT803d microphone. Participants wore a head-to-transducer stabilising headset designed by Articulate Instruments Ltd.

Annotation, tongue curve fitting, and normalization for time within Articulate Assistant Advanced followed the same procedure as that used in Zharkova (2016). The onset of the frication noise in the acoustic signal was taken as the consonant onset. Between three and nine children per group produced some preaspirated fricative tokens (in total, 26% of tokens). In those tokens, the preaspiration interval was not included in the consonant annotation. For every fricative token, the onset of the periodic signal following the consonant was taken as the consonant offset. Tongue curves were traced in each token for every ultrasound frame between frication onset and offset, i.e., at 10 ms intervals. The tongue curve tracing was carried out automatically, although manual correction was applied in most cases to the automatically tracked contours. The normalisation for time consisted in exporting, for each fricative token, *xy* coordinates for the tongue curves at nine equally spaced time points, with the first and the last point corresponding to the consonant onset and offset, respectively.

$LOC_{a\text{-}i}$ index (Zharkova *et al.*, 2015) was previously demonstrated to reliably distinguish between tongue shapes for /s/ and /ʃ/ in the vowel contexts of /a/ and /i/, that is, to quantify the differences between target fricatives in each of the two vowel contexts (Zharkova, 2016). In the present study, $LOC_{a\text{-}i}$ was calculated in R (R Development Core Team, 2013), using the scripts written by the first author, for every fricative token at each of the nine time points. The index value for a given tongue curve represents the difference between the excursion of the tongue front and the excursion of the tongue back. Illustrations of the index are provided in Fig. 1. In order to obtain the index value for a given tongue contour, a straight line is first traced between the two ends of the tongue curve. Two perpendiculars are then traced to the tongue curve, from the points located at one-third and two-thirds of the straight line between two ends of the curve (in Fig. 1, lines *f* and *b*, respectively). The index is a ratio of *f* to *b*. Higher $LOC_{a\text{-}i}$ values correspond to tongue shapes where the bunching occurs in the more anterior part of the tongue—note that the index does not provide information on the absolute position of the tongue within the vocal tract. For adults and preadolescent children speaking Scottish Standard English, $LOC_{a\text{-}i}$ has been shown to capture the differences between /ʃ/ and /s/ in the relative midsagittal bunching location. Specifically, Figs. 3 and 4 in Zharkova (2016) illustrate the predorsum bunching that characterises the former consonant [see also magnetic resonance imaging (MRI) images in Figs. 2 and 3 in Narayanan and Alwan, 1995, showing comparable differences in midsagittal tongue shape between postalveolar and alveolar sibilant fricatives in American English speakers' productions]. When describing differences in $LOC_{a\text{-}i}$ between the two fricatives in this study, we interpret the increase in the index values for /ʃ/ compared with /s/ as more bunching of the tongue predorsum, bearing in mind that the bunching for /ʃ/ may be accompanied by the predorsum raising towards the constriction location for the postalveolar fricative, and by posterior grooving (cf. coronal ultrasound data in Stone, 1991, illustrating this pattern). Since the index is a ratio, its values could be compared across speakers with different vocal tract sizes.

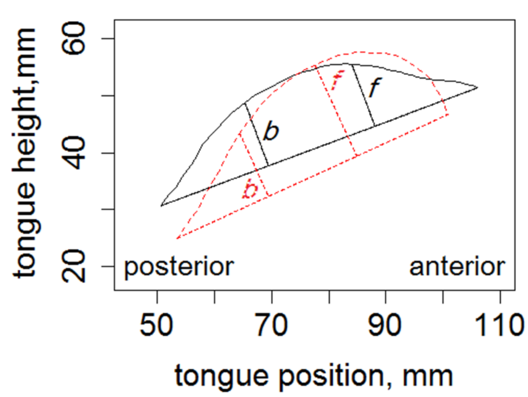

FIG. 1. (Color online) Illustrations of calculating $LOC_{a\text{-}i}$, based on the tokens produced by a seven-year-old speaker: mid-consonant for /s/ from /sa/ (solid) and /ʃ/ from /ʃa/ (dashed). The front of the tongue is on the right. The values of the index for these two curves are 0.98 for /s/ and 1.43 for /ʃ/.

Acoustic analysis was carried out in Praat (Boersma and Weenink, 2016) and in R (R Development Core Team, 2013). Audio files containing the fricative tokens were band-pass filtered in Praat, with the low and high cut-off frequencies of 300 Hz and 20 000 Hz, respectively. For the spectral analyses, we selected eight equal intervals between the consonant onset and offset, delimited by the nine equally spaced time points described above for the articulatory measurements. R scripts developed by Reidy (2013) and adapted by Romeo *et al*. (2013) were used for further acoustic analyses. For all band-pass filtered fricative tokens, at each of eight intervals, multitaper spectra (Thomson, 1982) were calculated, with eight orthogonal tapers, and the time-bandwidth parameter value $NW = 4$. No preemphasis was applied. The fricative centroid was then calculated for each token, using the multitaper spectra.

The two fricatives were compared to each other, as well as across contrasting vowel contexts, using original $\mathrm{LOC}_{\text{a-i}}$ and centroid values. Further comparisons included the following ratios derived from the original measurements. Discriminability between the two fricatives (Romeo *et al.*, 2013) was calculated for $\mathrm{LOC}_{\text{a-i}}$ and for the centroid within speaker for each vowel context and time point or interval. To compute discriminability, the difference between the mean values of the two consonant types was divided by the square root of the mean of the variances for the two fricatives. In the analysis of variability, the coefficient of variation (i.e., the ratio of the standard deviation to the mean) was computed, separately for $\mathrm{LOC}_{\text{a-i}}$ and for the centroid, for each speaker, consonant, vowel context, and time point or interval. In the analyses of discriminability in the context of /a/, the data from one 9-year-old child were not included, since this child only had three repetitions of /s/ from /sa/. In the analyses of variability, the data for /s/ from /sa/ produced by this nine-year-old child were excluded for the same reason. For comparing vowel-on-consonant influence across age groups, we first determined the mean $\mathrm{LOC}_{\text{a-i}}$ and centroid values for each speaker and consonant, for each timepoint or interval, separately in each vowel context. Coarticulation ratio was then calculated for each speaker, consonant, and timepoint or interval, as the ratio between the mean value of each dependent variable in the context of /i/ and the mean value of that variable in the context of /a/. Higher coarticulation ratio values represent greater vocalic effects.

A. Statistical analyses

R (R Development Core Team, 2013) was used for the statistical analyses. General additive mixed models (GAMMs; Wood, 2006; van Rij *et al.*, 2015) were carried out in order to analyse dynamic patterns of tongue shape and of the spectral centroid during the consonant.

1. GAMMs

GAMMs can identify a nonlinear relationship in the data over a period of time, using a number of nonlinear functions, while accounting for variability across speakers in the comparison groups. GAMMs can provide information on a constant difference between two levels of a factor over time, such as the higher, on average, $\mathrm{LOC}_{\text{a-i}}$ values for /ʃ/ than for /s/ in the context of /a/ in each age group, illustrated in Fig. 2. For identifying non-linear trends, the models include

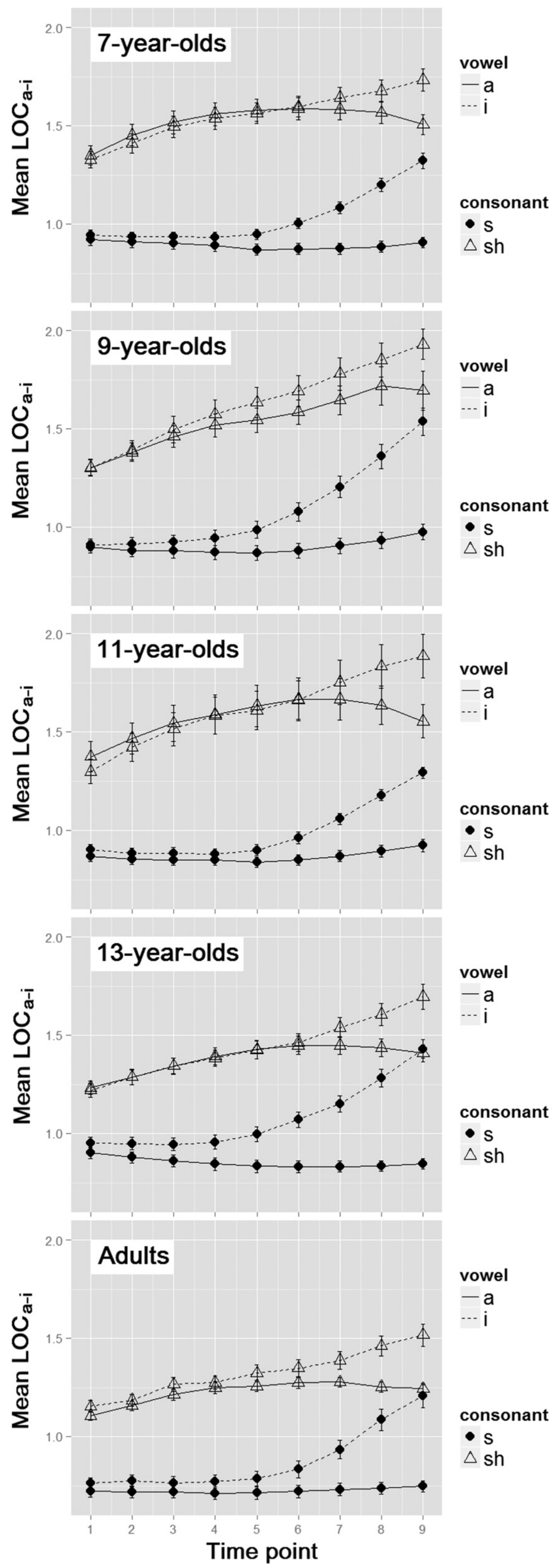

FIG. 2. Mean $\mathrm{LOC}_{\text{a-i}}$ values, with standard errors, for the five groups of speakers, plotted over the duration of the consonant, for each consonant in each vowel context.

"smooth" terms, which are used to establish any significant difference in the contrasting dynamic patterns, e.g., of the change in the relative location of tongue bunching during the consonant for /s/ across vowel contexts in all age groups, captured by $LOC_{a\text{-}i}$, also illustrated in Fig. 2. In this study, in order to incorporate the constant difference and the time-varying difference across the two levels of a factor (e.g., Consonant, Vowel, or Age Group), an ordered factor predictor was used, accompanied by a reference smooth, as well as an intercept term for the factor, i.e., a parametric coefficient representing the constant difference between the levels of the factor. The smooth with the ordered factor reflected the non-linear difference in trend over the course of the consonant between the two comparison groups. In each model, the intercept difference between the two levels of the factor was used to establish the presence of overall mean differences. In order to conclude that the comparison groups had different trends over time, the smooth with the ordered factor needed to be significantly different from zero.

2. Within-group comparisons

For the comparison of dynamic articulatory and acoustic patterns across the two fricative consonants, GAMMs were carried out on the dependent variables ($LOC_{a\text{-}i}$ and the fricative centroid, respectively) within age group. The models were run separately for each vowel context. Each model, for both articulatory and acoustic measures, included a random smooth for change over time by consonant within speaker, in order to account for individual differences in dynamic patterns. A Bonferroni adjustment was applied to adjust the significance level, based on ten within-group models focused on the cross-consonant difference (i.e., five age groups and two vowel contexts). Therefore, a given result was considered significant at the 0.05 level if its p value in the model was smaller than 0.005.

Within-group analyses of vowel-on-consonant influence over time were carried out separately for the two consonants, across the two contrasting vowels, otherwise following the above routine for the cross-consonant GAMMs.

3. Across-group comparisons

For the analyses of discriminability and coarticulation ratios, GAMMs were run across each pair of age groups for each vowel context and for each consonant, respectively. A random intercept for Speaker was included in each model. To establish the presence of age-related differences in variability, GAMMs were carried out on the coefficient of variation across each pair of age groups, separately for each CV syllable. In across-group analyses of discriminability and coarticulation ratios, Bonferroni adjustment was based on 20 individual models (i.e., ten pairs of age groups, and two vowel contexts or two consonants for the analyses of discriminability and coarticulation ratios, respectively). Consequently, a given result was considered significant at the 0.05 level if its p value in the model was smaller than 0.0025. For the analyses of variability, the adjusted p value was 0.00125, accounting for 40 individual models (ten pairs of age groups, two consonants and two vowel contexts).

III. RESULTS

A. Articulatory results

Figure 2 shows patterns of change in $LOC_{a\text{-}i}$ during the time course of the consonant in each age group. There is a clear difference across the two consonants for both vowel contexts and in all age groups. The cross-consonant difference tends to be somewhat smaller in the second half of the fricative in the context of /i/, due to the noticeable changes in tongue shape for /s/ before /i/ to accommodate the high front vowel influence. Vowel-related differences are noticeable for both consonants in all groups of speakers, with a gradual increase over the course of the consonant, particularly for the alveolar fricative. Specifically, the paths of $LOC_{a\text{-}i}$ change during the consonant diverge in the expected direction, with higher values in the context of /i/, and lower values in the context of /a/, representing consistent changes in the relative location of tongue bunching. For /ʃ/, this difference is noticeably smaller, and it is first apparent later than for /s/, across age groups.

The results of within-group across-consonant GAMMs on $LOC_{a\text{-}i}$, as well as the results of within-group models comparing each consonant across vowel contexts, are presented in Table I. For all age groups, the two consonants followed a significantly different pattern over time in tongue shape change, as the difference smooth was significant in each comparison. In the context of /a/, this cross-consonant difference was most evident in each age group in the predorsum bunching during the first half of /ʃ/, which was absent for /s/ (see Fig. 2). The figure also shows that in the context of /i/, the increase in $LOC_{a\text{-}i}$ occurred at different rates in the two consonants, relatively evenly for /ʃ/, while mostly in the second half of the consonant for /s/. $LOC_{a\text{-}i}$ values throughout the consonant were on average higher for /ʃ/ than for /s/ in both vowel contexts, with the intercept difference for Consonant significant in most of the models. A vowel-related difference in the pattern of tongue shape change over the course of /s/ was manifested in all groups of speakers, as shown by the fact that the smooth term was significant in every model. For /ʃ/, this difference was noticeably smaller than for /s/ in each age group, as shown by the cross-consonant differences in F values for the smooth term in the rightmost half of Table I; for the nine-year-old group the difference did not reach significance. The vowel-related difference in the intercept term only reached significance for /s/ in the adolescents.

Figure 3 presents mean group discriminability values for $LOC_{a\text{-}i}$ in each vowel context. Overall, discriminability is noticeably greater in the context of /a/ for every age group, particularly in the second half of the consonant, confirming the earlier observations on $LOC_{a\text{-}i}$ dynamics from Fig. 2.

Table II shows intercept term results from the GAMMs on $LOC_{a\text{-}i}$ discriminability, variability and coarticulation ratios. In the analyses of discriminability in the context of /a/, the youngest group had significantly smaller values than the adults. In the context of /i/, the seven-year-olds were different from the adults on the smooth term ($F = 5.888$, $p = 0.00245$), with the adults showing proportionately larger discriminability than the children at the beginning of the

TABLE I. The results of GAMMs on $LOC_{a\text{-}i}$ for every age group, across consonants and across vowel contexts. Significant results are in bold font; for each result, the relevant coefficient value (t for the intercept term; F for the smooth term) is above the p value. The alveolar consonant was used as a reference in the coding for the analyses of the difference between /s/ and /ʃ/, and the low vowel was used as a reference for the analyses of vowel-on-consonant influence, so positive t values mean that the consonant /ʃ/ and the context of /i/, respectively, had higher mean $LOC_{a\text{-}i}$ values.

	Difference between /s/ and /ʃ/				Vowel-on-consonant influence			
	Context of /a/		Context of /i/		/s/, /a/ versus /i/		/ʃ/, /a/ versus /i/	
	Intercept	Smooth	Intercept	Smooth	Intercept	Smooth	Intercept	Smooth
7yo	**9.868**	**15.224**	**7.835**	**7.846**	2.199	**35.776**	0.493	**7.457**
	<0.001	**<0.001**	**<0.001**	**<0.001**	0.028	**<0.001**	0.622	**<0.001**
9yo	**4.118**	**5.508**	**3.659**	**4.194**	0.002	**40.936**	0.705	3.617
	<0.001	**0.001**	**<0.001**	**0.0049**	0.999	**<0.001**	0.481	0.058
11yo	**7.751**	**12.199**	**7.813**	**5.187**	0.461	**40.047**	0.758	**6.578**
	<0.001	**<0.001**	**<0.001**	**0.001**	0.645	**<0.001**	0.449	**<0.001**
13yo	**13.630**	**28.673**	0.005	**6.205**	**3.886**	**67.052**	0.001	**15.820**
	<0.001	**<0.001**	0.996	**<0.001**	**<0.001**	**<0.001**	0.999	**<0.001**
Adult	**17.450**	**15.174**	0.042	**5.361**	0.018	**41.168**	1.567	**10.130**
	<0.001	**<0.001**	0.966	**<0.001**	0.986	**<0.001**	0.118	**<0.001**

consonant. The two youngest groups generally had smaller discriminability than the older groups, although most of those differences did not reach significance. The lack of significant across-group differences in the smooth term for discriminability in all but one model suggests that the general pattern was similar across age groups, with increased discriminability in tongue shape away from the beginning and end of the frication.

Mean variability was generally greater in younger than in older speakers, with the intercept results reaching significance for /ʃ/ from /ʃa/ in the comparisons between the seven-year-olds with the two oldest groups, as well as in the comparison between the 9- and 13-year-olds. The significantly larger variability in the youngest group than in the adults likely contributed to the significant age-related difference in discriminability; in the other cases, the increase in variability did not lead to a corresponding decrease in discriminability. The 7-year-olds had more variability than the 11-year-olds at the beginning of /s/ from /sa/ (the smooth term was significant; $F = 17.665$, $p < 0.001$), and also at the beginning of /ʃ/ from /ʃi/ in the comparison with the adolescents ($F = 11.515$, $p < 0.001$). The adults were less variable than the two youngest groups towards the end of /s/ from /si/ (the comparison with the 7-year-olds: $F = 6.497$, $p < 0.001$; the comparison with the 9-year-olds: $F = 7.864$, $p < 0.001$). The adolescents and the 11-year-old children did not show significantly larger variability than adults in any analyses.

In the GAMMs on coarticulation ratios, there were no significant age-related differences in the intercept term. In the comparison of /s/ coarticulation ratios between adolescents and 11-year-olds, the smooth term was significant ($F = 12.040$, $p < 0.001$), reflecting the fact that the adolescents had a greater increase in the vowel-related difference by the end of the consonant.

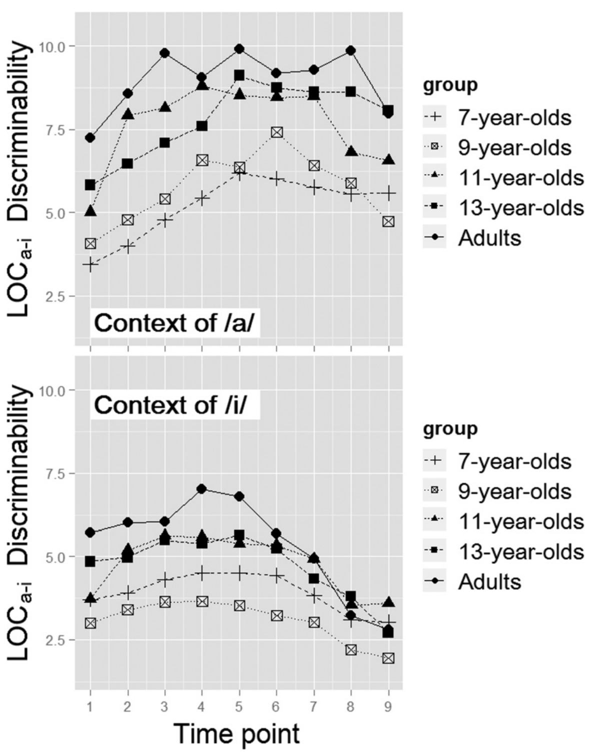

FIG. 3. Mean /s/-/ʃ/ $LOC_{a\text{-}i}$ discriminability values for each age group at every time point, separately for the two vowel contexts (the context of /a/ in the top panel, the context of /i/ in the bottom panel).

B. Acoustic results

Figure 4 shows the fricative centroid dynamic patterns during the consonant in each age group. Similar to the articulatory results, there is a clear difference across the two consonants for both vowel contexts, and in every age group. As illustrated in the figure, the mean centroid values are noticeably higher for /s/ than for /ʃ/ in all age groups, in both vowel contexts and at every interval. At the periphery of the consonant, the centroid values are lower than towards the middle of the consonant; this pattern is more noticeable for /s/, while for /ʃ/ the difference between the centre and the periphery of the consonant is smaller. Vowel-related differences are less noticeable in this figure than in Fig. 2 showing articulatory data. By contrast, more pronounced age-related changes in the cross-consonant patterns are shown

TABLE II. Results on the Age Group intercept term for the analyses of $LOC_{a\text{-}i}$ discriminability, variability, and coarticulation ratios. Significant results are in bold font; for each result, the t value is above the p value. The older age group member of the pair was used as a reference in each model. Thus, a negative sign of the t value indicates that the younger group in a given pair had a lower mean value than the older group in the pair, while a positive sign shows the opposite relationship.

	/s-ʃ/ discriminability		Variability				/i/ to /a/ ratio	
			Context of /a/		Context of /i/			
Age group	Context of /a/	Context of /i/	/s/	/ʃ/	/s/	/ʃ/	/s/	/ʃ/
7–9	−0.663	1.233	−0.055	−0.082	−1.088	−1.270	−0.161	−0.759
	0.508	0.219	0.956	0.934	0.278	0.206	0.873	0.449
7–11	−2.281	−0.915	1.554	2.111	0.145	−0.172	0.235	−0.337
	0.024	0.362	0.122	0.036	0.885	0.863	0.815	0.736
7–13	−2.293	−1.021	1.002	**5.592**	2.422	2.773	−1.199	−0.319
	0.023	0.309	0.318	**<0.001**	0.017	0.006	0.232	0.750
7-adult	**−3.114**	−1.547	1.044	**4.319**	1.888	1.031	−0.436	−0.742
	0.002	0.124	0.298	**<0.001**	0.061	0.304	0.664	0.459
9–11	−1.681	−1.950	1.091	1.595	1.047	1.003	0.405	0.397
	0.095	0.053	0.277	0.113	0.296	0.318	0.686	0.692
9–13	−1.719	−2.313	0.743	**3.361**	3.097	2.595	−1.055	0.514
	0.088	0.022	0.459	**<0.001**	0.002	0.010	0.293	0.608
9-adult	−2.527	−2.611	0.863	2.813	2.689	1.831	−0.299	−0.235
	0.013	0.010	0.390	0.006	0.008	0.069	0.765	0.815
11–13	−0.117	0.058	−0.458	2.073	1.629	1.894	−1.489	0.055
	0.907	0.954	0.647	0.040	0.105	0.060	0.138	0.956
11-adult	−0.948	−0.555	0.002	1.381	1.222	0.878	−0.655	−0.494
	0.345	0.580	0.999	0.169	0.224	0.381	0.514	0.622
13-adult	−0.809	−0.688	0.326	−0.820	−0.805	−1.896	0.602	−0.561
	0.420	0.493	0.744	0.413	0.422	0.060	0.548	0.576

in the acoustic results, with larger differences between the middle and the periphery of /s/ in older age groups.

The results of within-group GAMMs on the fricative centroid across consonants, as well as across vowel contexts, are presented in Table III. The two consonants followed a significantly different centroid pattern over time, as the smooth term was significant in each comparison, with the patterns for /s/ having a larger curvature. Somewhat higher values for the smooth term F in the older groups probably reflected age-related differences in the extent of centroid rise and fall at the periphery of the alveolar consonant compared with its centre. In most models, the two fricatives were on average different from each other in both vowel contexts, as shown by the intercept results. The higher values for the alveolar fricative reflect the cross-consonant difference in the lowest front cavity resonance, namely, the smaller cavity for /s/ than for /ʃ/ across age groups.

Effects from the contrasting vowels on each consonant in the GAMMs on the fricative centroid were different from the articulatory results across age groups. For /s/, neither the intercept term nor the smooth term reached significance after Bonferroni adjustment in any model. For /ʃ/, despite the higher mean centroid in the context of /i/ noticeable in the graphs in Fig. 4, the intercept term did not reach significance for any age group. The smooth term was significant in the 11- and 13-year-olds, reflecting a vowel-related difference in the last quarter of the consonant, namely, more centroid lowering in the context of /a/. A similar pattern could be discerned from the figure for the adults and the nine-year-old children, although the smooth term did not reach significance for those two age groups.

Figure 5 shows mean centroid discriminability over time for all age groups, separately for the two vowel contexts. Table IV presents GAMM results on the intercept term for discriminability, variability, and coarticulation ratios for the fricative centroid. Adults had a noticeably greater discriminability than the two youngest groups. As shown in the table, there were significant differences in the intercept term for discriminability between the adults and the nine-year-olds in both vowel contexts, as well as between the adults and the seven-year-olds in the context of /i/. The smooth term reached significance in both comparisons between the adults and the nine-year-olds (the context of /a/: $F = 5.880$, $p < 0.001$; the context of /i/: $F = 3.769$, $p = 0.00249$), as well as in the model comparing the seven-year-olds with the adults in the context of /a/ ($F = 6.156$, $p < 0.001$); in all those cases, during the first quarter of the consonant, adults had more differentiation between the two fricatives than children. The two oldest child groups had a smaller-than-adult discriminability in the low vowel context, although neither result reached significance after Bonferroni adjustment.

The generally greater centroid discriminability between the two fricatives in the adults than in the younger groups of children was due to noticeably greater centroid values for /s/ in the adults (see Fig. 4). Unlike the results reported above for $LOC_{a\text{-}i}$, there were no correspondences between discriminability and variability, suggesting that the larger centroid difference between the fricatives in the adults was

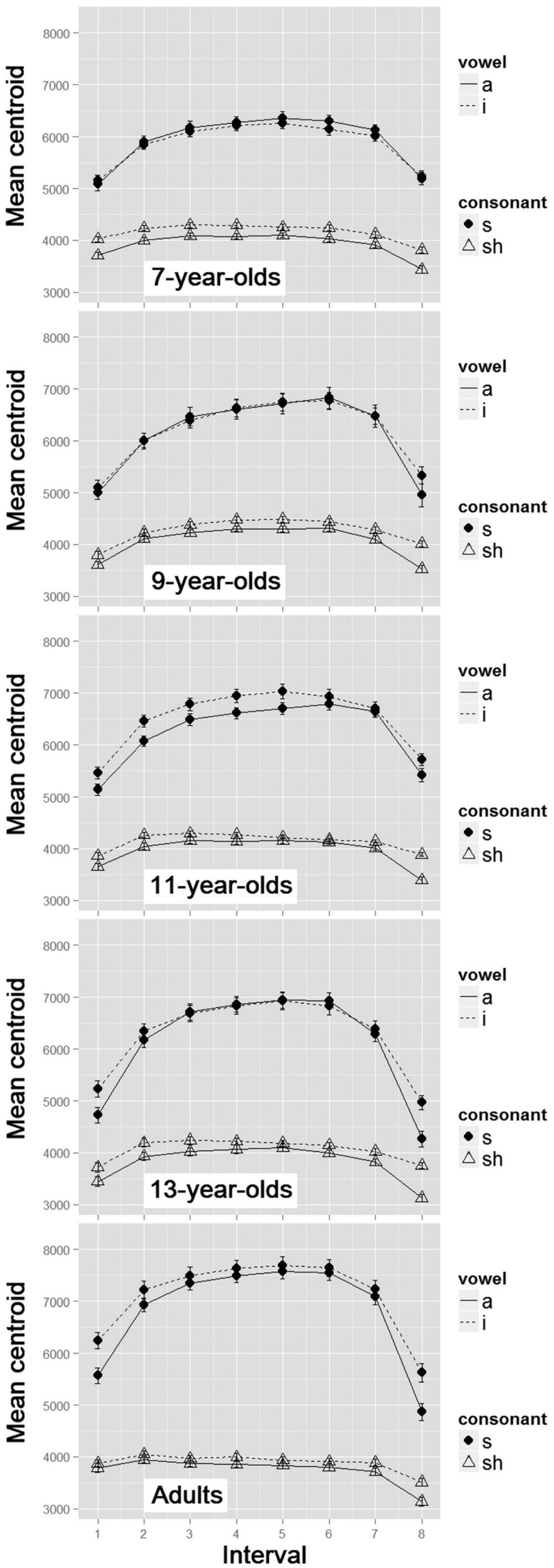

FIG. 4. Mean fricative centroid values, with standard errors, for the five groups of speakers, plotted over the duration of the consonant, for each consonant in each vowel context.

responsible for the age-related patterns more than any adult-child differences in variability. In fact, the only observed significant difference in variability was that in the smooth term for /s/ from /sa/ in the seven- to nine-year-old comparison ($F = 13.562$, $p < 0.001$), with a rise in the coefficient of variation towards the end of the consonant in most nine-year-olds, making them, as a group, more variable than the younger children.

Regarding the coarticulation ratio patterns, similarly to the articulatory results, most analyses did not yield significant across-group differences. The smooth term was significant in the 7- to 13-year-old comparison for /s/ ($F = 5.123$, $p = 0.00178$), with a larger vowel-related difference towards the end of the consonant for the adolescents. Similar patterns were observed in the comparisons for /s/ between the 11-year-olds and each of the two oldest age groups (11-year-olds versus adults: $F = 4.998$, $p = 0.00249$; 11-year-olds versus 13-year-olds: $F = 6.834$, $p < 0.001$), with both older groups showing a more noticeable increase in the vowel-related difference between the seventh and eighth interval than the 11-year-olds.

IV. DISCUSSION

This study reports original information on the patterns of tongue shape change, along with the spectral dynamics, from synchronised ultrasound and acoustic data on /s/ and /ʃ/ produced by children aged 7, 9, 11, and 13 years old. An articulatory index of the location of tongue bunching along the tongue contour, $\mathrm{LOC}_{\text{a-i}}$, differentiated between /s/ and /ʃ/ in all groups of children, as did the fricative centroid. There were significantly different patterns of change over the course of the consonant across the two fricatives, for both articulatory and acoustic measures, as well as some noticeable vowel-related differences conditioned by the contrasting vowels /a/ and /i/.

The finding that all children differentiated between the two fricatives on both articulatory and acoustic measures is in agreement with previous reports (e.g., Nittrouer *et al.*, 1989; Romeo *et al.*, 2013; Zharkova, 2016). Across age groups, there was evidence of more bunching of the front of the tongue for /ʃ/ than for /s/. This was particularly noticeable in the low vowel context, since the vowel /i/ involves the raising of the tongue front, thus somewhat obscuring the predorsum bunching involved in the production of the postalveolar fricative. On the spectral centroid, there were robust differences between the two fricatives, with higher values for /s/, reflecting the differences in the front cavity size. In all age groups and on both measures, the cross-consonant difference was reduced at the periphery of the consonant, compared with its middle part, particularly on the fricative centroid (see comparable results based on psychoacoustic spectral properties reported in Reidy, 2015).

The contrast between the periphery and centre of the fricative on the acoustic measure, observed for both /s/ and /ʃ/, reflects the jaw involvement in the articulation of the two consonants. The jaw contribution to the articulation of sibilant fricatives has previously been shown to be substantial in adults (using spectral and X-ray microbeam analyses in Iskarous *et al.*, 2011; EMMA analyses in Mooshammer *et al.*, 2007; spectral analyses in Reidy and Beckman, 2015) and children (spectral analyses in Reidy, 2015). Given that

TABLE III. The results of GAMMs on the fricative centroid for every age group, across consonants, and across vowel contexts. Significant results are in bold font; for each result, the relevant coefficient value is above the p value. Similarly to Table I, the alveolar consonant was used as a reference in the coding for the analyses of the difference between /s/ and /ʃ/, and the low vowel was used as a reference for the analyses of vowel-on-consonant influence.

	Difference between /s/ and /ʃ/				Vowel-on-consonant influence			
	Context of /a/		Context of /i/		/s/, /a/ versus /i/		/ʃ/, /a/ versus /i/	
	Intercept	Smooth	Intercept	Smooth	Intercept	Smooth	Intercept	Smooth
7yo	**−12.530**	**10.037**	−1.404	**8.267**	−0.018	0.030	0.000	1.321
	<0.001	**<0.001**	0.161	**<0.001**	0.985	0.862	1.000	0.262
9yo	**−7.359**	**10.168**	**−10.320**	**10.271**	0.613	0.675	1.664	2.523
	<0.001	**<0.001**	**<0.001**	**<0.001**	0.540	0.459	0.097	0.043
11yo	**−15.730**	**9.361**	**−21.720**	**17.142**	2.044	0.158	1.687	**5.787**
	<0.001	**<0.001**	**<0.001**	**<0.001**	0.041	0.691	0.092	**<0.001**
13yo	−2.241	**13.885**	**−10.690**	**18.027**	0.937	1.798	2.175	**4.359**
	0.025	**<0.001**	**<0.001**	**<0.001**	0.349	0.154	0.030	**0.002**
Adult	**−11.270**	**22.957**	**−15.830**	**27.260**	1.526	2.023	0.981	3.146
	<0.001	**<0.001**	**<0.001**	**<0.001**	0.127	0.111	0.327	0.023

one of the explanations for the significant jaw involvement in the fricative production is that it might facilitate lateral tongue bracing for the groove formation (Mooshammer *et al.*, 2007: 171), and motor control of the jaw matures earlier than that of the tongue (e.g., Green *et al.*, 2000; Zharkova *et al.*, 2014), all participants in our study could use the jaw to assist their lingual articulations. The contribution of the jaw appears to have increased with age, as suggested by the smooth term results for the centroid (Table III). In particular, this is illustrated in the pattern of the adults' production of /s/, where the centroid has a steeper rise and fall than for the younger speakers. This pattern might have been

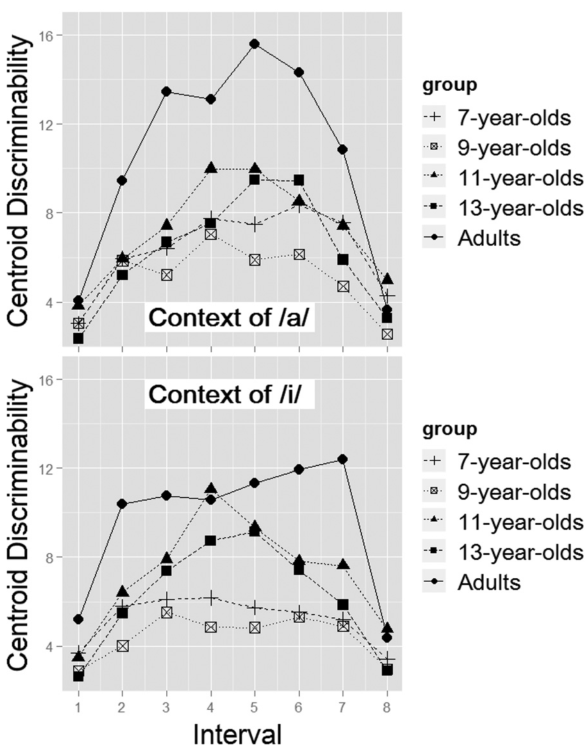

FIG. 5. Mean /s/-/ʃ/ centroid discriminability values for each age group at every interval, in the two vowel contexts (the context of /a/ in the top panel, the context of /i/ in the bottom panel).

due to the proportionately larger jaw displacement into and out of /s/ in the adults (cf. Iskarous *et al.*, 2011, where substantial jaw movement during /s/ from the preceding and into the following /a/ and /i/ was reported in American English speaking adults).

In all groups of speakers, vocalic effects were more noticeable in articulatory results. As can be seen from Table I, $\mathrm{LOC}_{\mathrm{a\text{-}i}}$ showed a more substantial vowel-on-/s/ than vowel-on-/ʃ/ influence (indeed, when GAMMs are run on $\mathrm{LOC}_{\mathrm{a\text{-}i}}$ coarticulation ratios across consonants, every age group shows significantly higher values for /s/ than for /ʃ/ during the second half of the consonant). For the fricative centroid, on the other hand, the only significant vowel effects in within-group GAMMs (see Table III) were observed for /ʃ/, but not for /s/. These contrasting cross-consonant patterns of articulatory and acoustic results are consistent with different levels of constraint on the tongue in the production of the two fricatives. For /ʃ/, the tongue tip does not touch the lower teeth, and the presence of a sublingual cavity may provide additional scope for changes in the consonant spectrum conditioned by the /a/-/i/ vowel pair, including potential changes due to jaw lowering in the context of /a/ (cf. MRI-based midsagittal images illustrating this articulatory pattern, in Fig. 8 of Proctor *et al.*, 2006). At the same time, there is a relatively small difference in the postalveolar consonant tongue shape conditioned by these two vowels, since a large proportion of the tongue is involved in making the constriction (see, e.g., midsagittal ultrasound images from productions by Scottish English speaking adults and preadolescents, in Zharkova *et al.*, 2014). By contrast, during the alveolar fricative, there are noticeable vowel-related changes in tongue shape over a larger proportion of the tongue length, with the least change at the alveolar zone, i.e., at the constriction location (cf. Table II in Recasens and Rodríguez, 2017). In our results for the alveolar fricative, even though within-group acoustic comparisons across vowel contexts did not yield significant results, mean group centroid values were often greater in the context of /i/ than in the context of /a/, particularly towards the end of the consonant, and those patterns were reflected in significant

TABLE IV. Results on the Age Group intercept term for the analyses of centroid discriminability, variability, and coarticulation ratios. Significant results are in bold font; for each result, the t value is above the p value. The older age group member of the pair was used as a reference in each model, similarly to Table II.

	/s-ʃ/ discriminability		Variability				/i/ to /a/ ratio	
			Context of /a/		Context of /i/			
Age group	Context of /a/	Context of /i/	/s/	/ʃ/	/s/	/ʃ/	/s/	/ʃ/
7–9	1.037	0.826	−2.548	0.392	−1.582	−0.699	−0.969	0.439
	0.302	0.410	0.012	0.696	0.116	0.486	0.334	0.662
7–11	−0.778	−1.666	−0.528	0.675	−0.071	0.603	−1.601	0.966
	0.438	0.098	0.598	0.501	0.944	0.547	0.112	0.336
7–13	0.126	−0.733	−2.599	0.584	−0.692	−1.618	−1.221	−0.551
	0.900	0.465	0.010	0.560	0.490	0.108	0.224	0.583
7-adult	−2.918	**−3.208**	−0.503	1.112	−0.010	0.463	−1.735	1.363
	0.004	**0.002**	0.616	0.268	0.992	0.644	0.085	0.175
9–11	−1.515	−2.572	2.175	0.276	1.709	1.389	−0.210	0.266
	0.132	0.011	0.031	0.783	0.090	0.167	0.834	0.791
9–13	−0.912	−1.454	0.131	0.022	1.073	−1.105	−0.042	−0.857
	0.364	0.148	0.896	0.983	0.285	0.271	0.967	0.393
9-adult	**−3.212**	**−4.152**	2.577	0.554	1.767	1.158	−0.374	0.593
	0.002	**<0.001**	0.011	0.581	0.079	0.249	0.709	0.554
11–13	0.856	0.751	−2.015	−0.317	−0.715	−2.196	0.212	−1.422
	0.393	0.454	0.046	0.752	0.476	0.030	0.833	0.157
11-adult	−2.067	−1.552	0.106	0.202	0.069	−0.100	−0.259	0.483
	0.041	0.123	0.916	0.840	0.945	0.921	0.796	0.630
13-adult	−2.941	−2.175	2.352	0.903	0.783	1.973	−0.417	1.759
	0.004	0.031	0.020	0.368	0.435	0.051	0.678	0.081

differences across age groups in acoustic coarticulation ratio comparisons (see below). Significantly greater frequency values for /s/ in high front rather than in low vowel contexts have been reported for English speaking adults by Reidy and Beckman (2015) using the most prominent psychoacoustic frequency as a measure of spectral dynamics. In an articulatory and acoustic study of fricative dynamics, Iskarous *et al.* (2011) reported significantly *smaller* centroid values for /s/ in high vowel contexts, and explained those findings by a smaller lip aperture for high vowels. One of the reasons behind the differences across the three studies could be that individual strategies of producing the alveolar fricative might affect inter-articulator coordination, and consequently vowel-on-/s/ coarticulatory patterns reflected in spectral characteristics. To establish if this is the case, future studies need to have more speakers and to collect three-dimensional articulatory data on both active and passive articulators. The vowel-related effects on the fricative centroid for /ʃ/ reported in Table III for two of the age groups in this study were in the same direction as those reported by Reidy and Beckman (2015), and these effects could have been due to differences in jaw position in anticipation of the high versus low vowel towards the end of the consonant frication (see a more detailed discussion below).

There was less discriminability across vowel contexts and on both acoustic and articulatory measures in the youngest age group than in adults as well as on the fricative centroid in the nine-year-olds than in adults. Differences in the same direction, i.e., with younger speakers having less discriminability, were observed on both measures in other across-group comparisons, albeit the results did not reach significance. Our findings agree with existing acoustic studies showing child-adult differences in discriminating between the two fricatives up to the age of seven years old (e.g., Nittrouer *et al.*, 1989; Nittrouer, 1995; Kleber, 2015). As shown by our results, these differences extend to the age of nine years (see also Maas and Mailend, 2017, where a smaller-than-adult acoustic differentiation between /s/ and /ʃ/ was reported for a group of nine-year-old typically developing children, but not for a group of six-year-olds). The results on $\mathrm{LOC}_{\text{a-i}}$ also suggest that up to the age of seven years, the differences are largely driven by the development of tongue control, with increased variability in tongue shape in younger children's productions leading to reduced discriminability on the articulatory measure. On both measures, 11-year-olds and adolescents discriminated between the two fricatives in a similar way to adults. Our findings are in agreement with some of the results reported by Romeo *et al.* (2013) on 9- to 14-year-old children and adults, where most children, except the nine-year-old girls, did not have significantly smaller fricative discriminability than adults. Romeo *et al.* (2013) analysed the fricative centroid based on the middle 50% of the consonant as opposed to multiple samples over time reported in our study, so this methodological difference might have made it possible in the present study to observe a general across-group difference on acoustic differentiation between nine-year-olds and adults.

Reduction in variability with increasing age, observed in numerous studies of child speech, has often been interpreted as a sign of neuromotor maturation (see, e.g., Smith, 2013). Age-related changes in within-speaker variability reported in our study were generally in the predicted direction, consistent with previous studies (e.g., Romeo *et al.*, 2013; Holliday *et al.*, 2015; Barbier, 2016) that show increased variability in children compared with adults. The patterns of variability were rather different across articulatory and acoustic results. For $LOC_{a\text{-}i}$, adults were significantly less variable than the two youngest groups of children on at least one CV combination (this description includes the significant smooth results, since they all demonstrated more variability in younger speakers somewhere during the consonant). Also, each of the two youngest groups was significantly more variable than the adolescents, again on at least one CV combination. The nine-year-olds were more variable than the seven-year-olds in the centroid results for /s/ from /sa/, with the smooth term reaching, and the intercept term approaching significance. The significantly greater variability in the nine-year-olds on the smooth term reflected the mean coefficient of variation values at the last interval of /s/ reaching above 0.15 for seven 9-year-olds, but only for two 7-year-old children. Examination of individual tongue movement patterns for the nine-year-olds during /s/ from /si/ (the comparison of $LOC_{a\text{-}i}$ variability for /s/ from /si/ between nine-year-olds and adults yielded a significant smooth term) provides additional information on variability in this child group. In particular, the pattern of tongue shape change over the duration of /s/ was not consistent across repetitions in five of the nine-year-olds, as shown by the presence of coefficient of variation values above 0.2 (absent in all the other nine-year-olds, as well as in most seven-year-olds). Those speakers were of both genders, and they had a wide distribution of ages within the overall nine-year-old age range. These patterns suggest that the articulatory variability in some nine-year-old participants might have been due to the unstable control of timing in the transition of the tongue from the consonant towards the target posture for the high front vowel, where a substantial amount of midsagittal tongue shape change is involved (see Zharkova, 2016). The increased variability in some of our nine-year-old children could be viewed as an illustration of the flexibility in the motor control system, which has to adapt to the ongoing craniofacial growth (Smith, 2013). This interpretation is consistent with a report by Vorperian *et al.* (2009), which noted an increase in the vocal tract growth rate from the age of eight years (preceded by a consistent decrease in growth rate from birth onwards), which would have resulted in additional demands on our nine-year-old speakers, compared with the younger group.

Our results on age-related patterns of vowel-on-consonant lingual coarticulation are not consistent with the idea of the extent of coarticulation indicating the size of production units (see Nittrouer *et al.*, 1989), since different patterns were observed for the two fricatives and across articulatory and acoustic measures, and there was no consistent increase or decrease in the amount of coarticulation with increasing age. Rather, our findings on anticipatory coarticulation enable us to gauge developmental changes in coordinating the movements of the tongue and other articulators relevant for producing voiceless sibilant fricatives. The results provide support for our prediction that all speakers would have some evidence of vowel-related adaptation to the consonant. The data on lingual articulatory dynamics for /s/ showed that in all age groups, the paths of tongue shape change in anticipation of the contrasting vowels diverged significantly during the consonant. For /ʃ/, this was the case for all age groups except the nine-year-olds. A possible reason for this pattern in the nine-year-olds is the relatively large articulatory variability in this age group, which was incorporated in the GAMMs. It could also be that the articulatory measure used in the study did not capture some of the vowel-related differences in tongue position (see a more detailed discussion below). The articulatory results for /s/ singled out the adolescent group, as this was the only group to show a significant effect on the intercept in Table I, as well as to have a greater increase in coarticulation by the end of the consonant than the 11-year-olds, as shown by the smooth result from the GAMM on coarticulation ratios. When we examined the data for individual speakers, the mean $LOC_{a\text{-}i}$ value for /s/ over five repetitions was consistently higher in the context of /i/ than in the context of /a/ for eight out of ten adolescents (four boys and four girls), while this was the case for only five 11-year-olds and four speakers in each of the other age groups. It would be interesting to include data from a larger number of speakers in future studies to find out how robust this pattern of increased vowel-on-consonant lingual influence is. Given that the rate of growth of the vocal tract increases between the ages of 8 and 14 years before starting to decrease after age 16 (Vorperian *et al.*, 2009), it might be hypothesised that the pattern we observed could extend further into adolescent years, until reducing in adulthood, reflecting the stabilisation of the motor control system (see also Romeo *et al.*, 2013).

Acoustic results on coarticulation ratios provide additional evidence of developmental changes in controlling articulators for the production of /s/, complementing the articulatory results. Specifically, the 13-year-olds had more vowel-related difference in the centroid towards the end of /s/ than the 11-year-old children, as shown by the smooth term results. Examination of acoustic coarticulation patterns by speaker shows that there was a rise in mean /i/-to-/a/ ratio values between the seventh and eighth intervals of /s/ for all adolescents except one, while this was the case for only six 11-year-olds. Further age-related differences in the acoustic patterns of /s/ coarticulation, namely, significant smooth differences between the adolescents and the youngest group as well as between the adults and the 11-year-olds, suggest that the coordination between the jaw and the tongue for producing the alveolar fricative may continue developing throughout childhood. For the postalveolar fricative, the 13- and 11-year-old groups stood out from all the other age groups on the centroid coarticulation results, with the smooth term for /ʃ/ (Table III) only significant in the 13- and 11-year-olds. This reflects a noticeable difference in the centroid across the two vowel contexts towards the end of the postalveolar consonant in these two age groups (see Fig. 4). This vowel-related difference could have been brought about by a relatively large jaw lowering for /a/ at the end of /ʃ/. A further contributor might have been the protracted coordination of lip rounding with the other articulator movements that are involved in the /ʃ/ production. The plausibility of the latter interpretation is supported by the findings of Smith and Zelaznik (2004), showing that coordination of jaw and lip movement differs between adults and adolescents. Both explanations are consistent with the fact that the rate of the vocal tract growth is increasing during preadolescent and early adolescent years, leading to adaptations in the motor control system (see Vorperian *et al.*, 2009; Smith, 2013). Overall, our results provide support for the interpretation of age-related patterns of vowel-on-consonant anticipatory coarticulation as indicating developmental maturation of coordinated control of articulators involved in producing speech rather than changes in the size of the planning unit.

Our results raise a methodological point related to quantifying vowel-on-consonant lingual coarticulation in children and adults, namely, that different ways of measuring coarticulation may capture different aspects of lingual activity. In Zharkova *et al.* (2014), using shortest curve-to-curve distances, a global difference between contrasting tongue postures for the fricatives /s/ and /ʃ/ across the vowel contexts /a/ and /i/ was shown to appear in the first half of the consonant for both adults and 10- to 12-year-old children (note that the adult data reported in the present paper constitute a subset of the adult data from that study). In a later study, a difference in $\mathrm{LOC}_{\text{a-i}}$ was not yet apparent by mid-/s/ in 11-year-old children, while for /ʃ/, this difference was not registered even in adolescents (Zharkova, 2018), suggesting that $\mathrm{LOC}_{\text{a-i}}$ quantifies more fine-grained changes than those captured by curve-to-curve distances. When the method of tongue curve analysis used in Zharkova *et al.* (2014) is applied to the data from the present study, the onset of vowel-on-consonant coarticulation is registered in adults at the first time point for both fricatives, while for the 11-year-olds, this method yields the onset of coarticulation by the second time point for /s/, and by the third time point for /ʃ/, making the overall picture quite similar to that described in our previous study. This observation has implications for comparing results on coarticulation development across studies using different methodologies (cf. a discussion on the use of measurements based on the whole tongue contour versus locus equations, in Barbier, 2016, p. 219). A related methodological point arising from our findings is that while $\mathrm{LOC}_{\text{a-i}}$ is clearly suited for quantifying /s/-/ʃ/ distinction in children and adults, some of the vowel-conditioned differences are less likely to be captured for the postalveolar fricative by this index than by other measures, such as curve-to-curve distances. We are currently working on developing further indices of tongue shape which would be more sensitive to the relevant changes in tongue shape of the postalveolar fricative, and would be applicable to ultrasound data from different age groups, including very young children.

The results presented in this paper contribute to the growing body of research findings calling for more dynamic analyses in interpreting natural speech variation (cf. Fuchs, 2017). The advantage of using dynamic information can be illustrated by an example of quantifying vowel-on-consonant coarticulation. We can compare different $\mathrm{LOC}_{\text{a-i}}$ results for our children's data on /s/, arrived at through analysing two different time points. Both these points have been used in previous studies of coarticulation in children: a time point located at 30 ms before the following vowel onset (e.g., Nittrouer *et al.*, 1989; Katz *et al.*, 1991), and a time point at mid-consonant, i.e., a relative rather than absolute time point (e.g., Zharkova *et al.*, 2011, 2012). Findings on $\mathrm{LOC}_{\text{a-i}}$ at mid-fricative, using the child dataset from the present study, were reported by Zharkova (2018), with the difference in $\mathrm{LOC}_{\text{a-i}}$ apparent by mid-/s/ for the adolescents, but not for any of the younger child age groups. When the same data on tongue shape are analysed at 30 ms before the vowel onset (this analysis is contingent on the lack of significant across-group differences in the duration of the fricative, which was indeed the case in our data), the vowel-on-/s/ effect is significant in every child age group. These two sets of findings provide complementary information, and interpreting each of them in the context of the dynamic patterns of tongue movement reported in the present study makes for a more accurate description.

Dynamic analyses of ultrasound images of the tongue, while providing rich and informative data, are very time consuming, as they involve tracing individual tongue curves, and require a significant amount of hand correction. Development of automatic methods of analysing dynamic ultrasound images without tongue contour tracking is ongoing (see, e.g., Hoole and Pouplier, 2017), and non-time-consuming automatic analysis of tongue contours in children's productions would be very welcome, particularly for working with large corpora of child speech (see Beckman *et al.*, 2017). An additional issue in analysing speech produced by very young children is that it is either very cumbersome or impossible to collect ultrasound data with adequate head stabilisation (or post-processing based on optical tracking), which is required for subsequent quantitative analyses not involving contour tracking, such as principal component analysis of raw ultrasound images. Therefore, automated techniques applied to dynamic ultrasound data collected without head-to-transducer correction would need to consider the requirement to correct for head-to-transducer displacement before the actual analysis of tongue movements. Until such techniques are introduced, articulatory measures like the one used in this study, which provide information on tongue shape change over time, and yet are not contingent on head-corrected recordings, are likely to prove useful in future studies of speech development in children.

ACKNOWLEDGMENTS

We are grateful to Steve Cowen for help with recordings and instrumentation, and to Pat Strycharczuk for advice on Praat scripting and on statistical analyses. The discussion on the use of dynamic versus single time point information in analysing coarticulation was inspired by a question from Mary Beckman at Ultrafest VIII conference in Potsdam. This research was supported by a grant from the Economic and Social Research Council (ES/K002597/1) to N.Z.

Articulate Instruments Ltd. (**2012**). *Articulate Assistant Advanced Ultrasound Module User Guide: Version 2.14* (Articulate Instruments Ltd, Edinburgh, UK), 69 pp.

Barbier, G. (**2016**). "Contrôle de la production de la parole chez l'enfant de 4 ans: l'anticipation comme indice de maturité mortice" ("Control of speech production in the 4-year-old child: Anticipation as an index of

motor maturity"), Ph.D. dissertation, l'Université Grenoble Alpes, Saint-Martin-d'Hères, France (in French).
Beautemps, D., Badin, P., and Bailly, G. (**2001**). "Linear degrees of freedom in speech production: Analysis of cineradio- and labio-film data and articulatory-acoustic modelling," J. Acoust. Soc. Am. **109**, 2165–2180.
Beckman, M. E., Plummer, A. R., Munson, B., and Reidy, P. F. (**2017**). "Methods for eliciting, annotating, and analyzing databases for child speech development," Comput. Speech Lang. **45**, 278–299.
Boersma, P., and Weenink, D. (**2016**). "Praat: Doing phonetics by computer (version 6.0.23) [computer program]," http://www.praat.org/ (Last viewed December 21, 2016).
Dodd, B., Holm, A., Hua, Z., and Crosbie, S. (**2003**). "Phonological development: A normative study of British English-speaking children," Clin. Ling. Phon. **17**, 617–643.
Forrest, K., Weismer, G., Milenkovic, P., and Dougall, R. N. (**1988**). "Statistical analysis of word-initial voiceless obstruents: Preliminary data," J. Acoust. Soc. Am. **84**, 115–123.
Fuchs, S. (**2017**). "Changes and challenges in explaining speech variation: A brief review," in *Fattori Sociali e Biologici Nella Ariazione Fonetica* (*Social and Biological Factors in Speech Variation*), edited by C. Bertini, C. Celata, G. Lenoci, C. Meluzzi, and I. Ricci (Officinaventuno, Milan, Italy), pp. 29–44.
Green, J. R., Moore, C. A., Higashikawa, M., and Steeve, R. W. (**2000**). "The physiologic development of speech motor control: Lip and jaw coordination," J. Speech Lang. Hear. Res. **43**, 239–255.
Holliday, J. J., Reidy, P. F., Beckman, M. E., and Edwards, J. (**2015**). "Quantifying the robustness of the English sibilant fricative contrast in children," J. Speech Lang. Hear. Res. **58**, 622–637.
Hoole, P., and Pouplier, M. (**2017**). "Öhman returns: New horizons in the collection and analysis of imaging data in speech production research," Comput. Speech Lang. **45**, 253–277.
Iskarous, K., Shadle, C. H., and Proctor, M. I. (**2011**). "Articulatory-acoustic kinematics: The production of American English /s/," J. Acoust. Soc. Am. **129**, 944–954.
Jongman, A., Wayland, R., and Wong, S. (**2000**). "Acoustic characteristics of English fricatives," J. Acoust. Soc. Am. **108**, 1252–1263.
Katz, W. F., Kripke, C., and Tallal, P. (**1991**). "Anticipatory coarticulation in the speech of adults and young children: Acoustic, perceptual, and video data," J. Speech Hear. Res. **34**, 1222–1232.
Kleber, F. (**2015**). "Direction of coarticulation in vowel-fricative sequences in L1-German children," in *Poster at the Child Phonology Conference*, June 24–26, St. John's, Canada.
Koenig, L. L., Lucero, J. C., and Perlman, E. (**2008**). "Speech production variability in fricatives of children and adults: Results of functional data analysis," J. Acoust. Soc. Am. **124**, 3158–3170.
Li, F., Edwards, J., and Beckman, M. E. (**2009**). "Contrast and covert contrast: The phonetic development of voiceless sibilant fricatives in English and Japanese toddlers," J. Phon. **37**, 111–124.
Li, F., and Munson, B. (**2016**). "The development of voiceless sibilant fricatives in Putonghua-speaking children," J. Speech Lang. Hear. Res. **59**, 699–712.
Maas, E., and Mailend, M.-L. (**2017**). "Fricative contrast and coarticulation in children with and without speech sound disorders," Am. J. Speech Lang. Pathol. **26**, 649–663.
McLeod, S. (**2013**). "Speech sound acquisition," in *Articulation and Phonological Disorders: Speech Sound Disorders in Children*, 7th ed., edited by J. E. Bernthal, N. W. Bankson, and P. Flipsen, Jr. (Pearson, Boston, MA), pp. 58–113.
Mooshammer, C., Hoole, P., and Geumann, A. (**2007**). "Jaw and order," Lang. Speech **50**, 145–176.
Munson, B. (**2004**). "Variability in /s/ production in children and adults: Evidence from dynamic measures of spectral mean," J. Speech Lang. Hear. Res. **47**, 58–69.
Narayanan, S. S., and Alwan, A. A. (**1995**). "An articulatory study of fricative consonants using magnetic resonance imaging," J. Acoust. Soc. Am. **98**, 1325–1347.
Nittrouer, S. (**1995**). "Children learn separate aspects of speech production at different rates: Evidence from spectral moments," J. Acoust. Soc. Am. **97**, 520–530.
Nittrouer, S., Studdert-Kennedy, M., and McGowan, R. S. (**1989**). "The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults," J. Speech Hear. Res. **32**, 120–132.
Proctor, M., Shadle, C., and Iskarous, K. (**2006**). "An MRI study of vocalic context effects and lip rounding in the production of English sibilants," in *Proceedings of the 11th Australian International Conference on Speech Science & Technology*, December 6–8, Auckland, New Zealand, pp. 307–312.
R Development Core Team (**2013**). "R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing [computer program," http://www.R-project.org (Last viewed May 16, 2013).
Recasens, D., and Rodríguez, C. (**2017**). "Lingual articulation and coarticulation for Catalan consonants and vowels: An ultrasound study," Phonetica **74**, 125–156.
Reidy, P. F. (**2013**). "An introduction to random processes for the spectral analysis of speech data," Ohio State Univ. Working Papers Ling. **60**, 67–116.
Reidy, P. F. (**2015**). "The spectral dynamics of voiceless sibilant fricatives in English and Japanese," Ph.D. thesis, The Ohio State University, Columbus, OH.
Reidy, P. F., and Beckman, M. E. (**2015**). "Vowel context effects on the spectral dynamics of English and Japanese sibilant fricatives," J. Acoust. Soc. Am. **137**, 2381.
Romeo, R., Hazan, V., and Pettinato, M. (**2013**). "Developmental and gender-related trends of intra-talker variability in consonant production," J. Acoust. Soc. Am. **134**, 3781–3792.
Smith, A. (**2013**). "Development of neural control of orofacial movements for speech," in *The Handbook of Phonetic Sciences*, 2nd ed., edited by W. J. Hardcastle, J. Laver, and F. E. Gibbon (Wiley-Blackwell, Chichester, West Sussex, UK), pp. 251–296.
Smith, A., and Zelaznik, H. N. (**2004**). "Development of functional synergies for speech motor coordination in childhood and adolescence," Dev. Psychobiol. **45**, 22–33.
Stone, M. (**1991**). "Toward a model of three-dimensional tongue movement," J. Phon. **19**, 309–320.
Thomson, D. J. (**1982**). "Spectrum estimation and harmonic analysis," Proc. IEEE **70**, 1055–1096.
Van Rij, J., Wieling, M., Baayen, R. H., and van Rijn, H. (**2015**). "itsadug: Interpreting time series and autocorrelated data using GAMMs. R package, version 0.8 [computer program]," https://cran.r-project.org/web/packages/itsadug/index.html (Last viewed August 28, 2017).
Vorperian, H. K., Wang, S., Chung, M. K., Schimek, E. M., Durtschi, R. B., Kent, R. D., Ziegert, A. J., and Gentry, R. (**2009**). "Anatomic development of the oral and pharyngeal portions of the vocal tract: An imaging study," J. Acoust. Soc. Am. **125**, 1666–1678.
Wood, S. N. (**2006**). *Generalized Additive Models: An Introduction With R* (CRC Press, Boca Raton, FL).
Zharkova, N. (**2016**). "Ultrasound and acoustic analysis of sibilant fricatives in preadolescents and adults," J. Acoust. Soc. Am. **139**, 2342–2351.
Zharkova, N. (**2018**). "An ultrasound study of the development of lingual coarticulation during childhood," Phonetica **75**, 245–271.
Zharkova, N., Gibbon, F. E., and Hardcastle, W. J. (**2015**). "Quantifying lingual coarticulation using ultrasound imaging data collected with and without head stabilisation," Clin. Ling. Phon. **29**, 249–265.
Zharkova, N., Hewlett, N., and Hardcastle, W. J. (**2011**). "Coarticulation as an indicator of speech motor control development in children: An ultrasound study," Motor Control **15**, 118–140.
Zharkova, N., Hewlett, N., and Hardcastle, W. J. (**2012**). "An ultrasound study of lingual coarticulation in /sV/ syllables produced by adults and typically developing children," J. Int. Phon. Assoc. **42**, 193–208.
Zharkova, N., Hewlett, N., Hardcastle, W. J., and Lickley, R. J. (**2014**). "Spatial and temporal lingual coarticulation and motor control in preadolescents," J. Speech Lang. Hear. Res. **57**, 374–388.